

## First physics results from the HARP experiment at CERN

A. Cervera Villanueva  
*University of Geneva, Switzerland*



The first physics results of the HARP experiment are presented. We emphasize the high performance of the forward part of the apparatus. The differential raw pion yield and its efficiency correction up to polar angles of  $250\text{ mrad}$  are shown. The analysed setting is  $12.9\text{ GeV}/c$  incident protons in a 5% interaction length aluminium target.

### 1 Introduction

The HARP experiment<sup>1</sup> was designed to perform a systematic and precise study of hadron production for beam momenta between  $1.5$  and  $15\text{ GeV}/c$ , for target nuclei ranging from hydrogen to lead. The detector was located at CERN, in the PS beam, and took 420 million events during the years 2001 and 2002.

The physics goals of HARP are to make a measurement of the pion yield that will enable a quantitative design of the proton driver of a neutrino factory, and to improve the precision of atmospheric neutrino flux calculations. In addition, the energy-range is suitable to measure particle yields for the prediction of neutrino fluxes for the MiniBooNE<sup>4</sup> and K2K<sup>5</sup> experiments ( $8.9$  and  $12.9\text{ GeV}/c$  respectively). To this end a collaboration was set up with these groups. Beam energy settings and dedicated targets were used to provide the most relevant measurements.

A schematic layout of the apparatus is shown in Fig. 1. It is a large acceptance spectrometer, with two distinct regions. A forward region (up to polar angles of about  $250\text{ mrad}$ ), where the main tracking devices are a set of drift chambers, and where particle identification is possible thanks to the combination of a threshold cerenkov, a time-of-flight wall and an electron identifier. In the large-angle region the main tracking and particle-id detector is a TPC, which is complemented by a set of RPC detectors for time of flight measurements. In addition, a complex beam instrumentation was set up in order to establish the nature of the incoming particle, given the rather impure beam. The main subsystems are three small timing detectors and two

cerenkovs. The beam time detectors are also used to estimate the interaction time at the target, located inside the TPC.

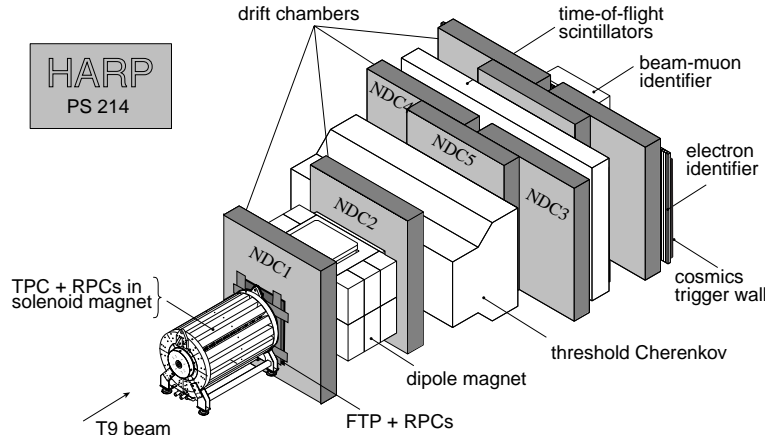


Figure 1: Schematic layout of the HARP spectrometer.

Given the immediate interest of the MiniBooNE and K2K experiments in our results, the HARP Collaboration has decided to start the data analysis with these two attractive items. In particular, we present in this article a first analysis of the data dedicated to the K2K measurement, using for this purpose the forward region of the detector, which is able to cover by itself the K2K requirements.

The organisation is as follows. Section 2 introduces the motivation of this analysis. In section 3 the tracking capabilities of the forward spectrometer are presented. Section 4 is devoted to the particle identification subsystems and their performance. Finally, the data analysis is presented in section 5 and the conclusions in section 6.

## 2 Motivation of this analysis

One of the main systematic errors on the neutrino oscillation parameters measured by the K2K experiment comes from the uncertainty on the far/near neutrino flux ratio. This ratio depends on the differential pion production cross section, which is essentially measured by a threshold cerenkov (pion monitor) above  $E_\nu = 1 \text{ GeV}$ , but must rely on Monte Carlo simulations below that energy. Unfortunately, the oscillation peak is located at  $E_\nu \sim 0.55 \text{ GeV}$ . HARP could precisely estimate the pion differential cross section at these energies and subsequently reduce that systematic error.

Fig. 2-left shows the  $(p, \theta)$  distribution for pions producing neutrinos in the bin containing the oscillation peak ( $0.5 - 0.75 \text{ GeV}$ ). The relevant phase space is  $1 < p < 8 \text{ GeV}$  and  $\theta < 250 \text{ mrad}$ , which is fully covered by HARP's forward region as shown in Fig. 2.

3.5 million useful events were taken by HARP with incident  $12.9 \text{ GeV}/c$  protons and an exact replica of the K2K target, which is a  $80 \times 3 \text{ cm}$  aluminum tube (2 interaction lengths). Another 6M events were collected with a  $5\% \lambda$  aluminium target ("K2K thin target") and a similar beam in order to decouple reinteraction and absorption effects from pure production. The data analysis presented in this article is based on this particular setting.

## 3 Forward Tracking

Tracking of forward going particles is done by a set of drift chambers (NDC) placed upstream and downstream of the dipole magnet (DIP). The NDC-DIP combination allows the momentum

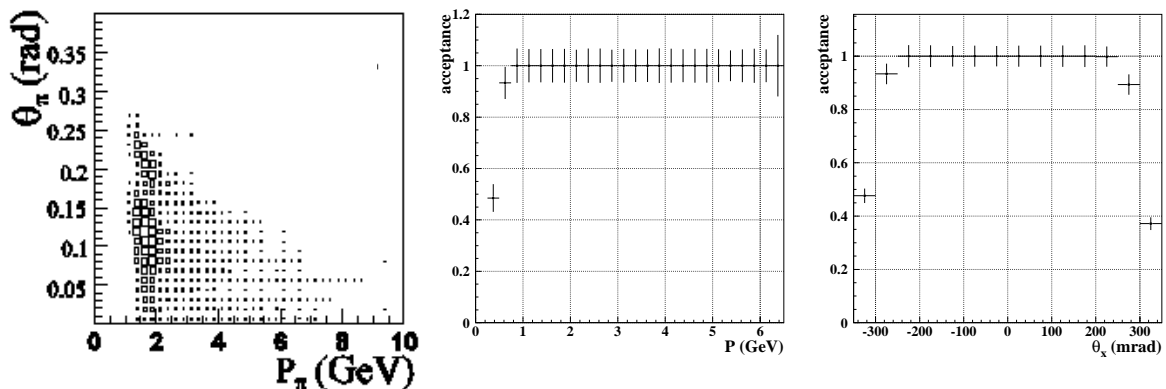


Figure 2: On the left,  $(p, \theta)$  distribution for pions producing neutrinos in the bin containing the oscillation peak ( $0.5 - 0.75$  GeV). This figure is a courtesy of the K2K Collaboration. It has been obtained with a full simulation of the K2K pion production and decay chains. Center and right, geometrical acceptance of HARP's dipole magnet for particles arriving to the first NDC module (NDC1). On the center,  $P$  dependence for particles with  $|\theta_x| < 200$  mrad. On the right,  $\theta_x$  dependence for particles with  $P > 1$  GeV/c.

measurement by matching track segments located at either side of the magnet.

The chambers were recuperated from the NOMAD experiment and their properties have been described elsewhere<sup>2</sup>. Each NDC module contains 4 chambers, and each chamber 3 planes of wires with tilted angles  $-5^\circ$ ,  $0^\circ$  and  $5^\circ$ . The single wire efficiency is of the order of 80%, and the spatial resolution approximately  $340 \mu\text{m}$ .<sup>a</sup>

The reconstruction algorithm builds  $2D$  and  $3D$  track segments in each NDC module (12 hits maximum), which are fitted to a straight line model via a Kalman Filter fit<sup>6</sup>. Afterwards, all the possible matching combinations of tracking objects (including unused hits) belonging to different modules are performed in order to obtain longer tracks.

The momentum measurement is done associating  $3D$  downstream segments with  $3D$  and  $2D$  segments in the upstream module (NDC1). This asymmetry is needed to compensate the low tracking efficiency of the upstream chambers, due to the presence of a unique module and to the higher hit density (proximity to the target), which provokes pattern recognition confusion. Fig. 3-bottom shows the momentum and angular resolutions for  $3D$ - $3D$  up-down matches.

The small track separation in NDC1 induces a huge correlation between particles that implies a hadron model dependent tracking efficiency. This is a potential source of systematic error as shown in Fig. 3-top. The average efficiency is of the order of 65% when one considers only  $3D$ - $3D$  up-down matches. The situation improves when  $2D$ - $3D$  matches are included. Recent studies with a third type of tracks, built by matching a  $3D$  downstream track with the vertex, show a considerable efficiency recovery. As these tracks are independent of NDC1, the total efficiency ( $3D$ - $3D$  +  $2D$ - $3D$  + *vertex*- $3D$ ) is nearly model independent.

#### 4 Particle Identification

Particle identification in HARP's forward region uses the information from the time of flight system (TOF), the threshold cerenkov (CKOV) and the electron identifier (EID). Pion/proton separation is provided by TOF up to  $4.5$  GeV/c, and by the CKOV above  $3$  GeV/c. Elec-

<sup>a</sup>The chambers had a superior performance in NOMAD (95% hit efficiency and a resolution a factor of two better). This is mainly due to the use of different non-flammable gas mixture ( $Ar(90\%) - CO_2(9\%) - CH_4(1\%)$ ), and voltage settings (sense wires held at +1300V and potential wires at -2900V). However, one should stress that this spatial resolution is more than sufficient for HARP physics

tron/pion separation is covered by the CKOV below 3  $GeV/c$  and by the EID above 2  $GeV/c$ . Finally the kaon contamination can be estimated with the CKOV above 3  $GeV/c$  and with the (TOF) below this energy.

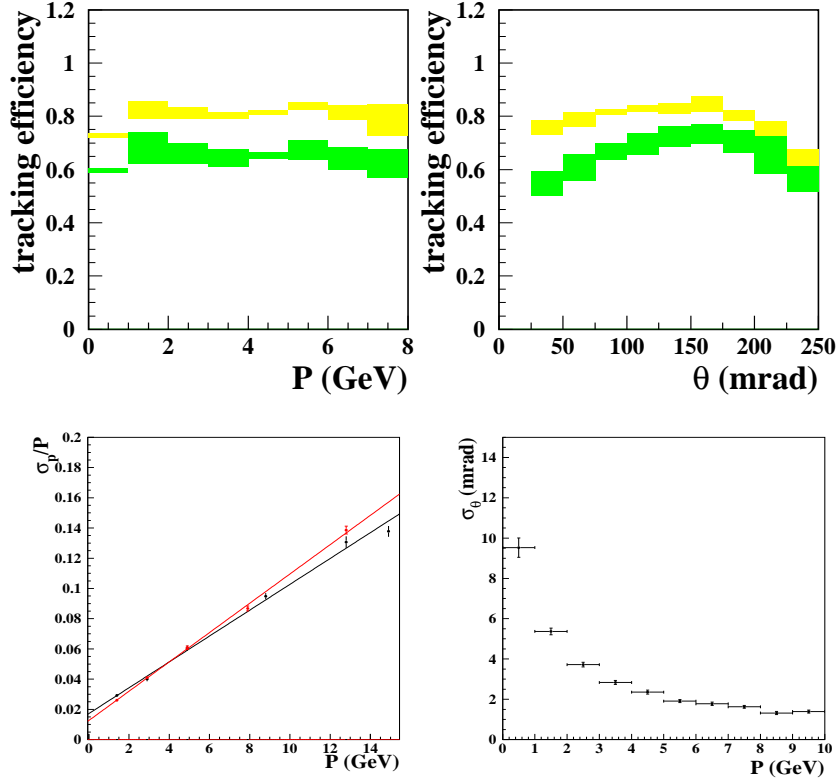


Figure 3: On the top, tracking efficiency as a function of momentum (left) and angle (right). The bands represent the maximum difference between 3 Monte Carlo hadron generators (MC1, MC2, MC3). The lower band corresponds to 3D-3D up-down matches while the upper band includes also 2D-3D up-down matches. On the bottom-left, momentum resolution for data (dark) and Monte Carlo (light). On the bottom-right, angular resolution for Monte Carlo. Both correspond to 3D-3D matches, with no vertex constraint included.

#### 4.1 Time of Flight System

Particle identification by time of flight in HARP's forward region relies on the combination of particle momenta ( $p$ ) and track length ( $L$ ), measured with the forward spectrometer, and the time-of-flight between a start signal ( $t_0$ ) from the beam time detectors and a stop signal ( $t_w$ ) from the TOF wall, placed at about 10 meters downstream from the target. The mass of a particle can be computed from these quantities,  $m^2 = p^2 \cdot [((t_w - t_0) \cdot c/L)^2 - 1]$ .

The current TOF wall and  $t_0$  resolutions are 150 and 70  $ps$  respectively. However, the  $t_0$  resolution used for the analysis shown in this paper was above 200  $ps$ , leading to a combined TOF resolution of about 270  $ps$ , which is already better than the design value of 300  $ps$ .

The TOF is able to provide a  $\pi/p$  separation of  $\sim 5\sigma$  at 3  $GeV/c$ , as can be seen in Fig. 4-left. In practice, the TOF system will provide reasonable  $\pi/p$  separation up to 4.5  $GeV/c$ . The  $\pi/k$  capabilities of the detector at low energies ( $<3$   $GeV/c$ ) are being studied at the moment<sup>b</sup>.

<sup>b</sup>It has been recently proposed to use unbiased golden events (all beam time detectors firing to gain in  $t_0$  resolution) and tracks (crossing the overlap region between counters in the TOF wall to increase the  $t_w$  resolution) in order to estimate the  $\pi/k$  ratio below 3  $GeV/c$ . The  $t_0$  resolution obtained in this case is close to 130  $ps$ . Anyway, the kaon contamination at these energies is known to be very small.

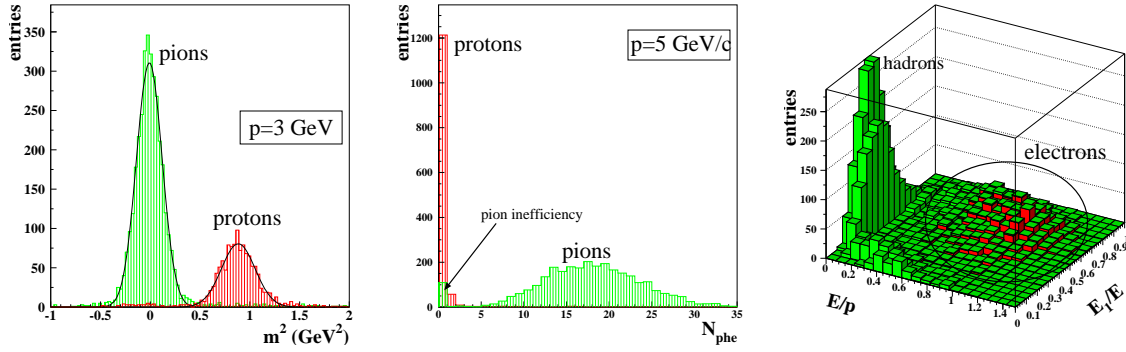


Figure 4: On the left, mass squared as measured by the TOF system for 3  $GeV/c$  beam particles. On the center, photoelectron yield in the cerenkov produced by beam pions, electrons and protons in a 5  $GeV/c$  no target run. On the right, hadron and electron yields as a function of  $E_1/E$  and  $E/p$  for beam particles in a 3  $GeV/c$  no target run.  $E$  is the sum of the energies deposited in the two calorimeter modules ( $E_1 + E_2$ ) and  $p$  is the momentum. In all cases pure samples are selected using the beam detectors.

#### 4.2 Threshold cerenkov

The cerenkov detector is able to identify electrons below the  $\pi$  saturation ( $\sim 4 GeV/c$ ). Pions and electrons can be separated from protons and kaons below the kaon threshold at  $\sim 9 GeV/c$ , and protons can be discriminated above this energy. Fig. 4-center shows the photoelectron yield for beam pions, electrons and protons in a 5  $GeV/c$  no target run. At 5  $GeV/c$  pions are close to the saturation regime and cannot be distinguished from electrons, which on the other hand are very rare at these energies. However,  $\pi/p$  separation is highly pure and efficient at 5  $GeV/c$  (and above).

#### 4.3 Electron identifier

The electron identifier is made of two calorimeter planes reused from the CHORUS experiment and described elsewhere<sup>3</sup>. It was designed to provide electron-pion separation when low energy ( $< 3 GeV/c$ ) charged pions, accompanied by knock-on electrons, are occasionally identified as electrons by the cerenkov counter. It also serves to identify electrons at high energy, when the cerenkov has lost its pion/electron separation capabilities. The detector performance is summarised in Fig. 4-right.

### 5 The analysis

One sixth ( 1 million events ) of the “K2K thin target” data has been analysed. The unnormalised pion production differential cross section can be computed as follows<sup>c</sup>:

$$\sigma_i^\pi = \frac{1}{\varepsilon_i^{acc}} \frac{1}{\varepsilon_i^{track}} \frac{1}{\varepsilon_i^\pi} \eta_i^\pi \cdot N_i^\pi, \quad (1)$$

where the index  $i$  corresponds to  $(p, \theta)$  bins.  $\varepsilon_i^{acc}$  is the geometrical acceptance,  $\varepsilon_i^{track}$  is the tracking efficiency,  $\varepsilon_i^\pi$  is the pion identification efficiency,  $\eta_i^\pi$  is the pion purity and  $N_i^\pi$  is the observed pion yield. The pion purity is defined as  $\eta_i^\pi = (N_i^\pi - N_i^{bkg})/N_i^\pi$ , where  $N_i^{bkg}$  is pion misidentification background. Fig. 5 shows the raw pion yield corrected by the tracking and pion identification efficiencies ( $\frac{1}{\varepsilon_i^{track} \cdot \varepsilon_i^\pi} N_i^\pi$ ) as a function of  $p$  and  $\theta$ .

<sup>c</sup>Bin migration effects are not considered for the moment. Preliminary studies show a small effect.

The current activities in the context of this forward analysis follow the line of recovering tracking efficiency by using the matching between the downstream tracks and the vertex. The most recent results obtained with the improved tracking are very encouraging as they are nearly model independent. This will allow a considerable reduction of the systematic error.

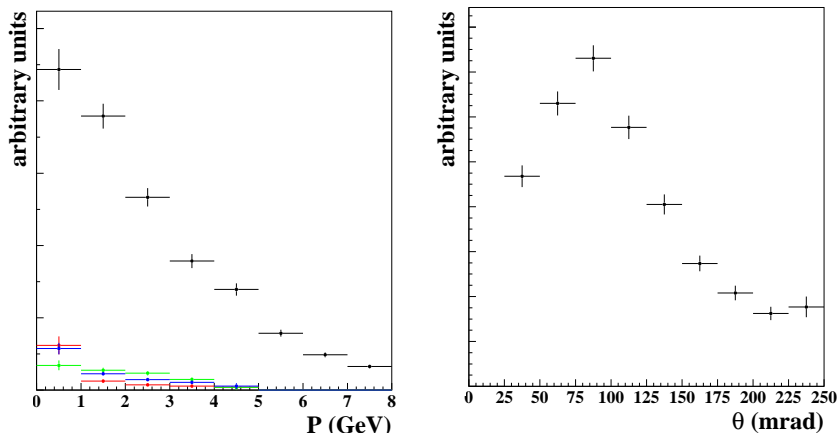


Figure 5: Raw pion yield corrected by tracking and pion identification efficiencies. On the left, the  $p/\pi$  misidentification background for the TOF system is also shown (for the three hadron generators). The number of Monte Carlo events used to compute the tracking efficiency was of the order of 50000. This explains the large statistical errors in these figures.

## 6 Conclusions

We have described the current performance of the HARP apparatus and our first physics analysis. This analysis is based on specific data taken by HARP to improve the neutrino flux calculation for the K2K experiment. Particle identification and tracking of forward going particles is well under control. This has permitted an initial estimation of the differential raw pion yield and its efficiency correction. The analysis is still in progress and will lead to conclusive results shortly.

## Acknowledgments

I would like to thank the whole HARP Collaboration for their help and support. Special thanks to our K2K and MiniBooNE colleagues, Issei Kato, Linda Coney, Geoff Mills and Dave Schmitz, who have intensely collaborated to produce these results. I'm also grateful to Malcolm Ellis for his invaluable help, including the English corrections of this article.

## References

1. The HARP Collaboration, CERN-SPSC/2003-027, SPSC-P-325
2. M. Anfreville *et al.*, *Nucl. Instrum. Methods A* **481**, 339 (2002).
3. The CHORUS Collaboration, *Nucl. Instrum. Methods A* **378**, 221 (1996).
4. <http://www-boone.fnal.gov/publicpages/runplan.ps.gz>
5. M.H. Ahn *et al.*, The K2K Collaboration *Phys. Rev. Lett.* **490**, 041801 (2003).
6. R. Fröhlich *et al.*, *Nucl. Instrum. Methods A* **262**, 444 (1987).